Systems Engineering
&
Effectiveness Analysis

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Outline

1.0 Aspects of Systems Engineering

2.0 Systems Engineering Process: Hierarchy of the five Ds

3.0 System development models

4.0 Systems Effectiveness

5.0 Effectiveness Factors

6.0 Systems Effectiveness Analysis (SEA)

7.0 Conclusion.

Systems Engineering

Systems engineering is a multidisciplinary subject dealing with the integration of all parts of a system (hardware, software, and operator) into the real world environment. It provides rationalization for tradeoffs in meeting the requirements and building the system.

Why Systems Engineering is Important

- It provides a balanced and disciplined approach for the integration of the system into the user environment.
- It focuses on objectives, the measurement of accomplishments, and provides insights into complex operational issues.
- It provides a systematic approach to sort issues in a disciplined manner and to identify areas for tradeoffs: cost, quality, performance, reliability, interoperability, availability, effectiveness, security, and extensibility.

Aspects of Systems Engineering

- There are four overlapping aspects: philosophical, management and business, operational, and technical and engineering

Philosophical Aspect

- It is concerned with the theory and concept of S.E.
- It deals with the life cycle hierarchy and sequence of the five Ds: Definition, Development, Design, Deployment, and Disposal
- System Development Models
  - Waterfall Model
  - Spiral Model
  - Vee Model
  - SE-Interactive Model
- Stages and phases of the Systems Engineering process

Management and Business Aspect

It is concerned with the application of management and business disciplines: planning, budgeting, costing, schedule control, system acquisition, project management, resource allocation, and program evaluation.

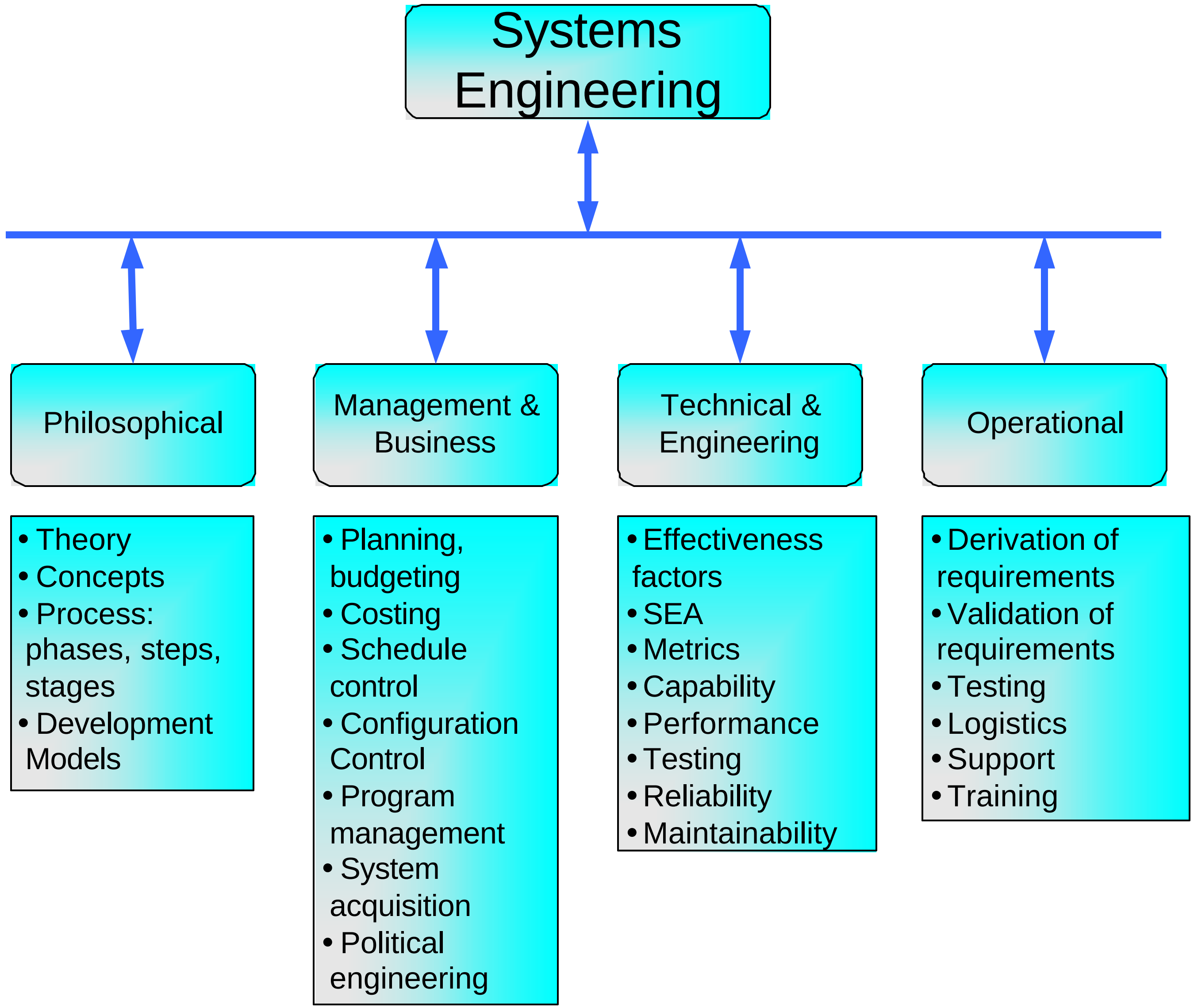
Operational Aspect

- It is concerned with the determination and validation of the requirements, testing, training, logistics, and support.

Technical and Engineering Aspects

- Follows a disciplined series of steps focusing on: objectives, system analysis, effectiveness, design, development, and integration.
- Systems effectiveness analysis
- Cost-Benefit analysis
- System architecture – functionalities and structure
- System integration
- Selection of metrics
- Tradeoff analysis
- System performance specification
- Design Specification
- Validation and testing

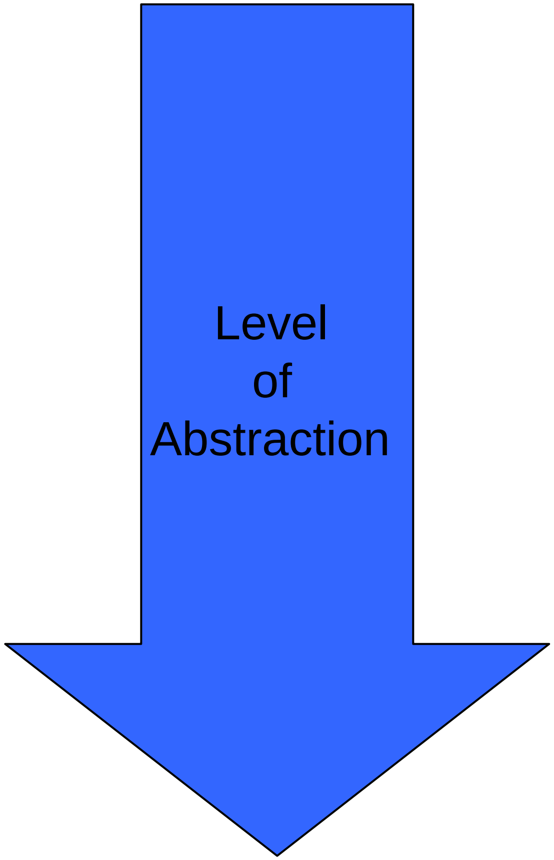
Systems Engineering Framework



Systems Engineering Process

- There are several models of systems engineering process with many variations
  - (1) Waterfall Model
  - (2) Spiral Model
  - (3) Vee Model
  - (4) Systems Engineering Interactive Model

Systems Engineering Process Flow: Requirements to Realization



1 Requirements

2
- Systems Analysis
- Functionalities
- System Performance Specification

3
- Systems Architecture, Function and Structure
- Assessment

4
- System Design and Development

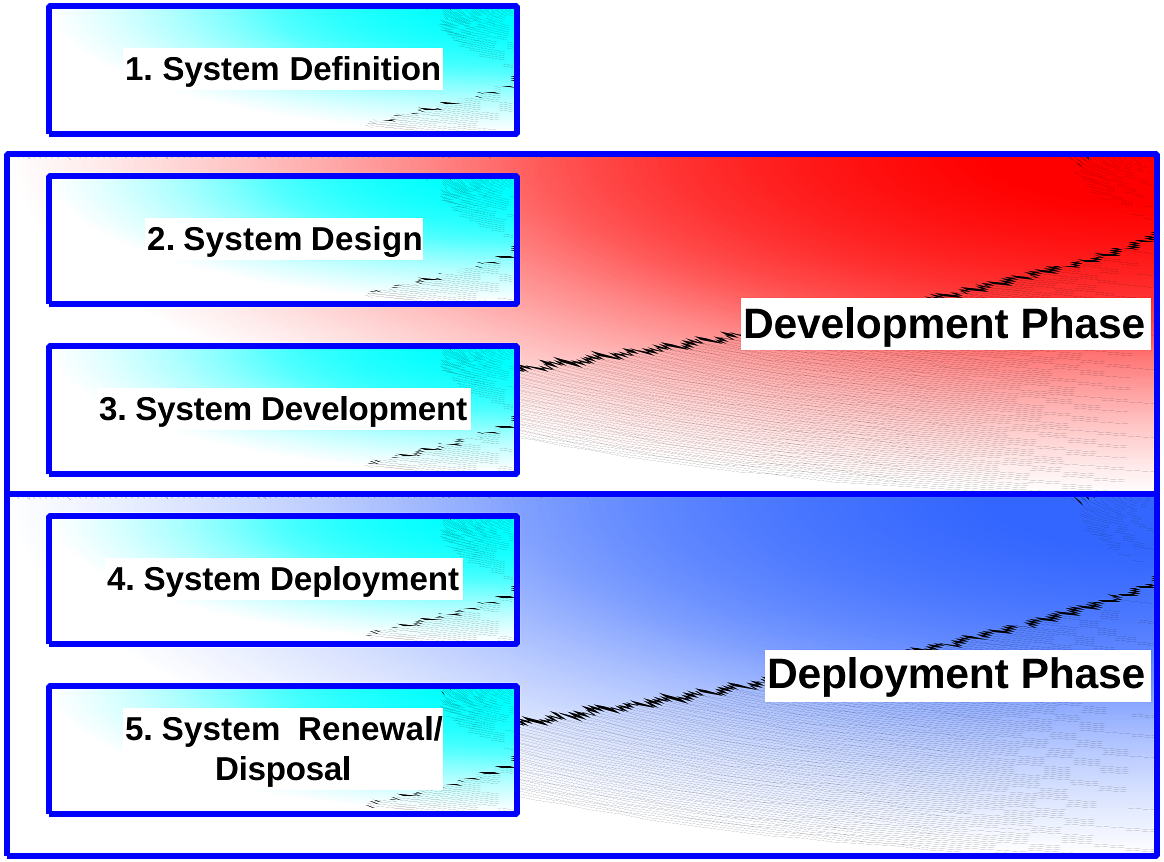
5
- System Integration
- Design Specification

6
- Verification
- Testing

7 Realization

Systems Engineering Life Cycle

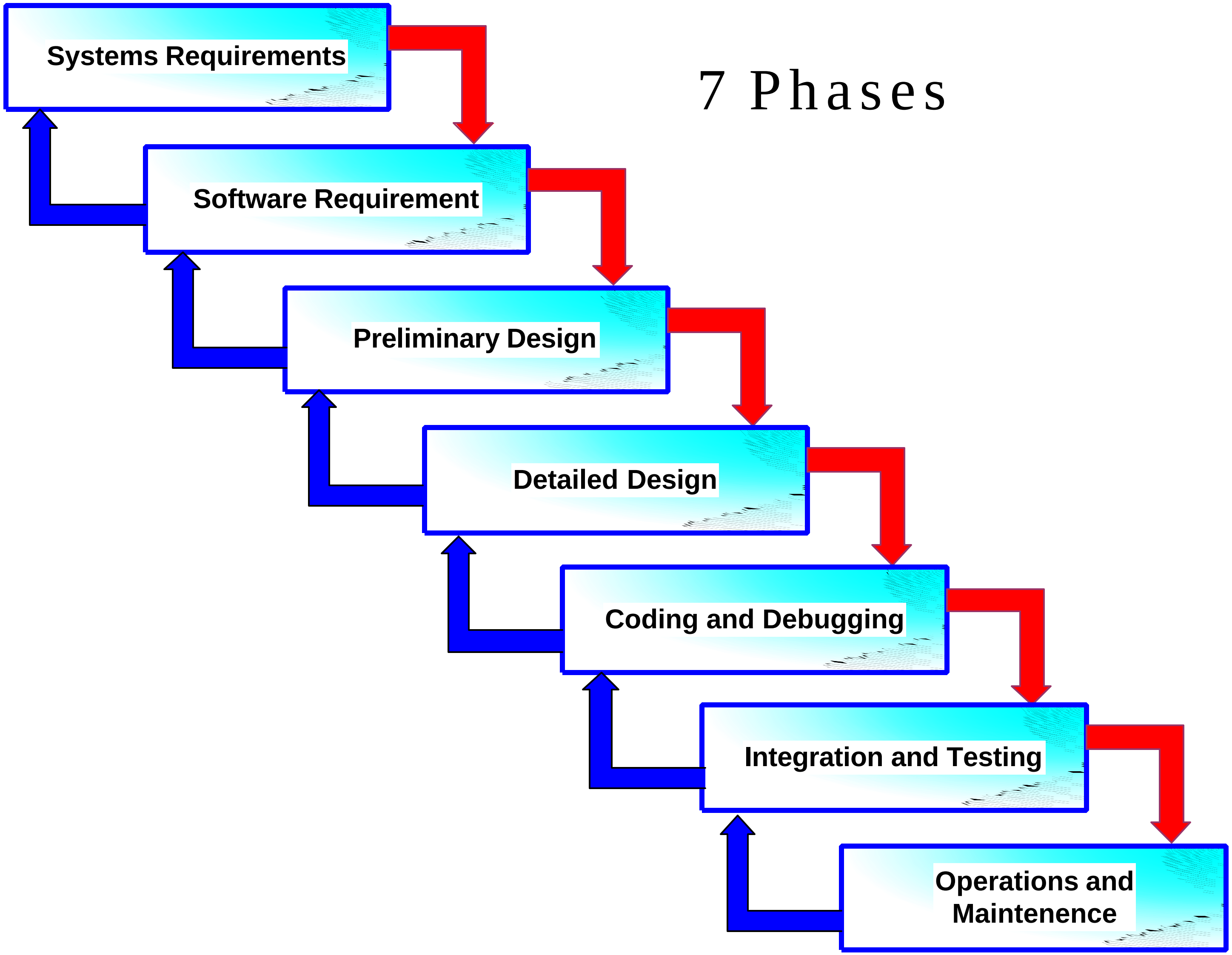
- Systems have a life-cycle hierarchy of Five Structured Levels: 5Ds



Waterfall Model

- Earliest software engineering process introduced by Royce, W.W. 1970, called “Waterfall model” by Boehm, B.W. 1976
- The model is characterized by the sequential flow down of life-cycle phases
- It allows iteration only between adjacent phases
- It is the basis for Mil. Std. 2167A for software development
- It is appropriate when the requirement is clear and specific and the development is low risk

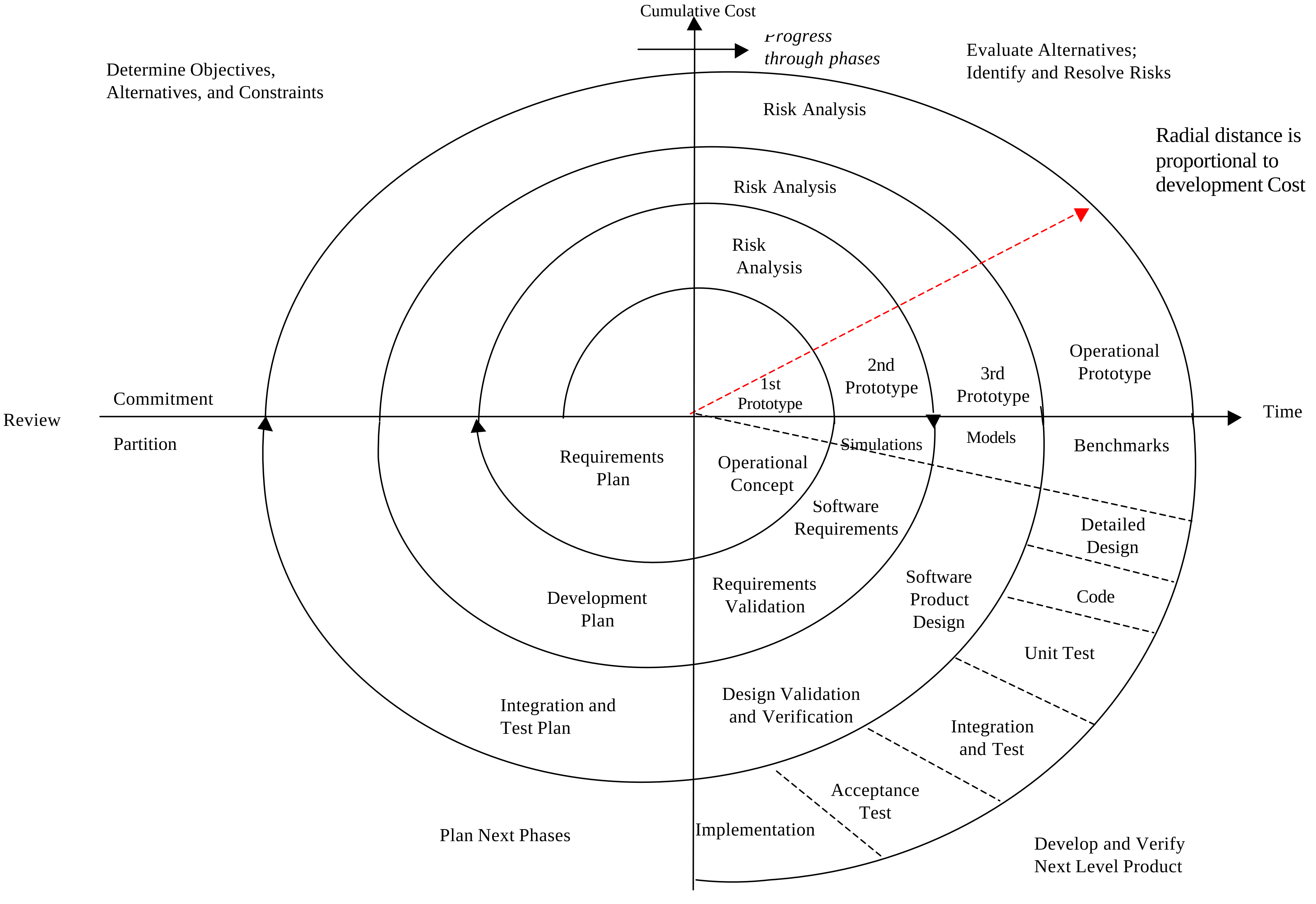
Waterfall Model of Software Engineering



Spiral Model

- Developed in the 1980s by Boehm and Papaccio
- Modified several times in 1986 and 1988
- Tailored for high risk development
- It has four phases: (1) Design, (2) Evaluation and Risk analysis, (3) Development, (4) Testing and Planning
- Starts with the identification of the objectives, constraints, and alternative design
- Emphasis is on Evaluation and Risk analysis
- Development is considered a prototype activity, which provides mock-ups of the software or system
- The number of iterations around the spiral is variable

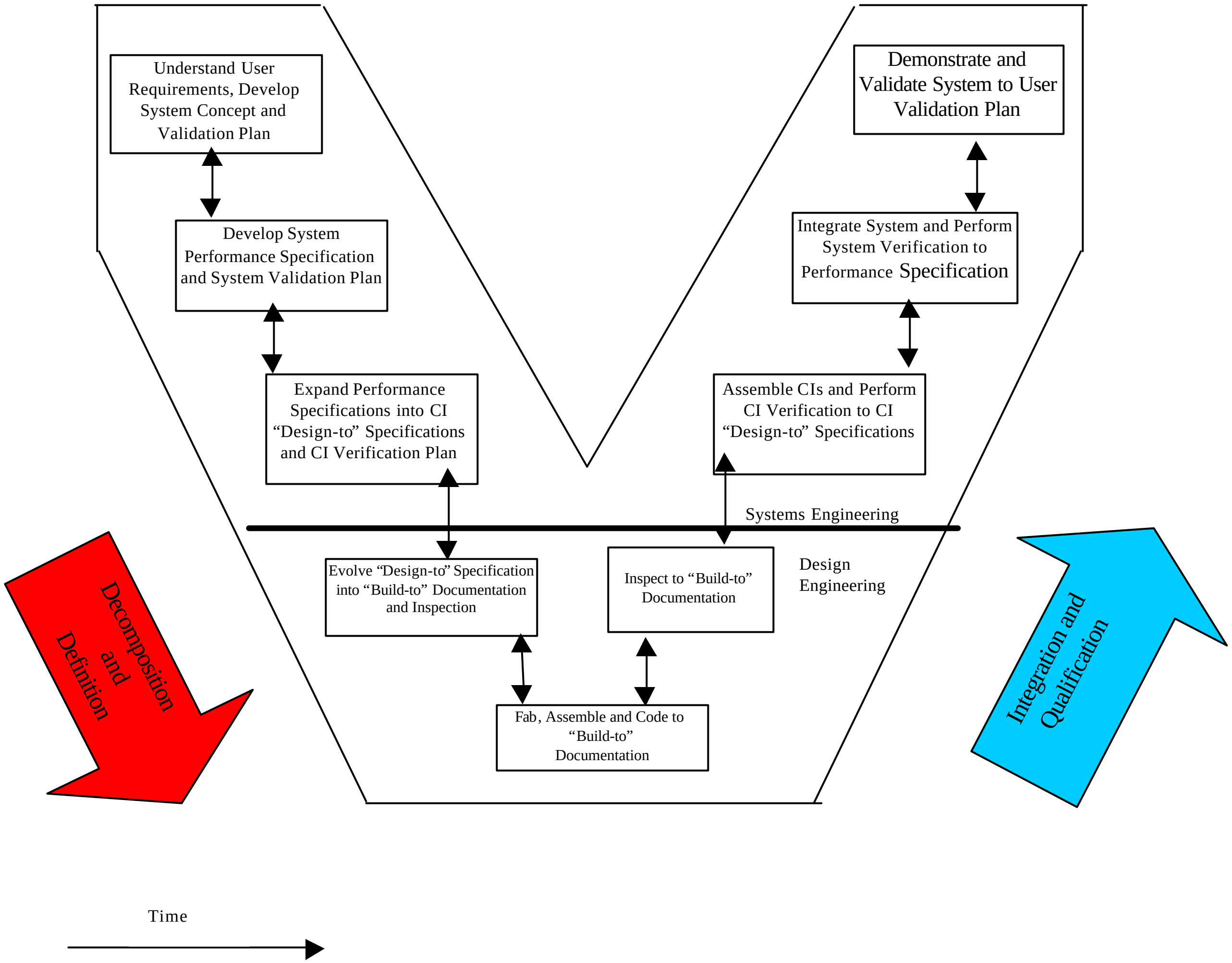
Spiral Model



Vee Model

- Introduced in 1992 by Forsberg and Mooz
- Emphasis is on engineering activities
- Starts with the definition of operational needs
- Focus is on the transition from operational needs to system specification to design specification
- Left hand side depicts decomposition and definition
- Right hand side represents integration and qualification activities

Vee Model



CI-Configuration Item

Systems Engineering Interactive Model

- It follows the 5Ds sequence
- It allows for interaction between the definition, development, and deployment phases
- Results from evaluations and tests are used to improve the specificity of design and requirements.

Systems Engineering Interactive Model

System Definition

Requirements/Objectives
Requirements Analysis
Mission Analysis
System Performance

Preliminary Conceptual Design

Requirements Loop

System Development

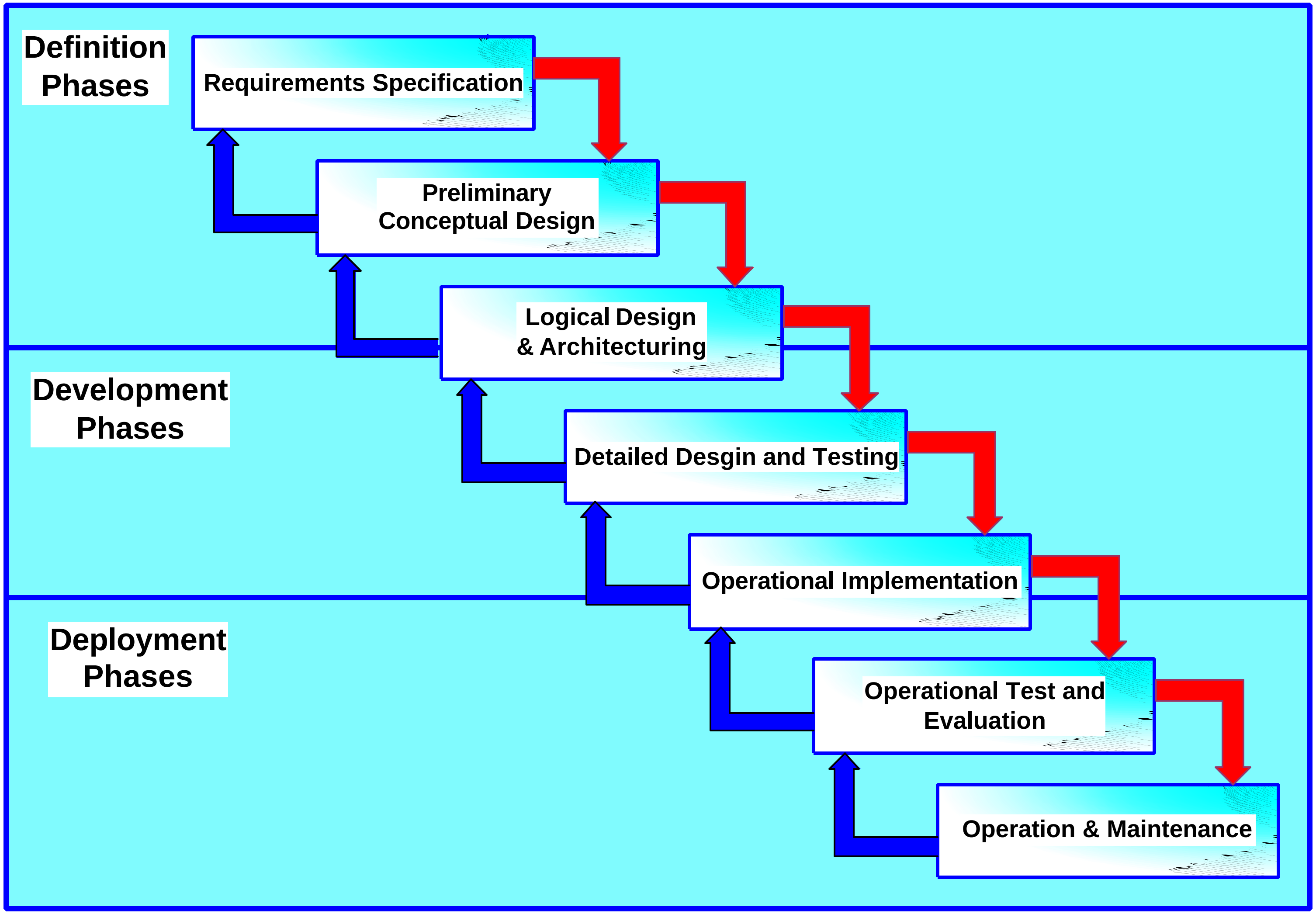
- System Effectiveness Analysis
- MOEs, MOPs
- Functional Requirements
- Tradeoffs Analysis
- Technology Base
- System Design and Architecturing
- System Integration

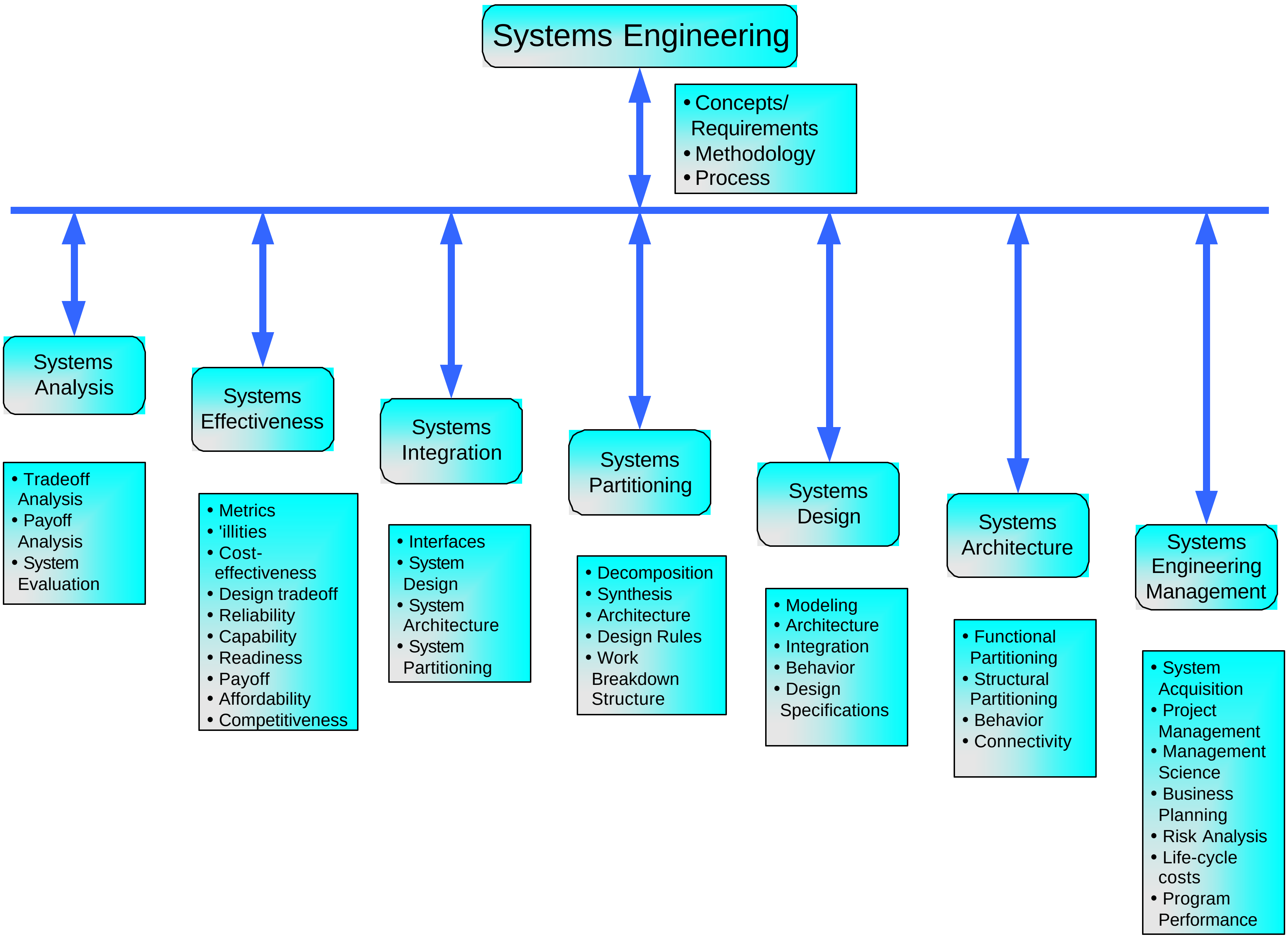
Design Loop

System Deployment

- Detailed Design and Testing
- Transform System Architecture into Real World Entities: Functional and Physical
- System Design Specifications and Standards
- Operational Implementation
- Operational Test and Evaluation
- Operation and Maintenance

Seven Phases of Systems Engineering Process For Acquisition or Production




Systems Engineering
• Concepts/ Requirements
• Methodology
• Process
Systems Analysis
• Tradeoff Analysis
• Payoff Analysis
• System Evaluation
Systems Effectiveness
• Metrics
• 'illities
• Cost-effectiveness
• Design tradeoff
• Reliability
• Capability
• Readiness
• Payoff
• Affordability
• Competitiveness
Systems Integration
• Interfaces
• System Design
• System Architecture
• System Partitioning
Systems Partitioning
• Decomposition
• Synthesis
• Architecture
• Design Rules
• Work Breakdown Structure
Systems Design
• Modeling
• Architecture
• Integration
• Behavior
• Design Specifications
Systems Architecture
• Functional Partitioning
• Structural Partitioning
• Behavior
• Connectivity
Systems Engineering Management
• System Acquisition
• Project Management
• Management Science
• Business Planning
• Risk Analysis
• Life-cycle costs
• Program Performance

Systems Effectiveness

Why Systems Effectiveness?

- Increased demand for:
  - More performance
  - Competitiveness
  - Quality
  - Lower cost (life cycle costs)
  - More efficiency (productivity)
  - Limited resources and test data
  - Winning

Why System Effectiveness?

continued

- Need for a comprehensive methodology to optimize integration and resource allocation of personnel, hardware, software, and procedures
- Identify and quantify problem areas
- Tradeoff Analysis

History

- In 1914 F.W. Lanchester applied analytical techniques to the fuzzy area of policy and strategy formulation:
  - Tradeoff Aeroplane versus Dirigible
- WWI and WWII gave impetus to military operations and analysis
  - How best to use Aircraft?
  - How best to use Radar?
  - How best to use Tanks?

Effectiveness

- Effectiveness is a desired result, outcome, consequence, or operation
- Effectiveness is doing the right thing right, to achieve the objective (hopefully from the first time)

Systems Effectiveness Concept

* S.E. is a measure of the ability of the system to accomplish its objective
* It is a measure of the extent to which a system can be expected to achieve a set of specific goals
* It can also be thought of as the probability P_{se} that the system will achieve its objective

System Effectiveness Quantification

- Due to multiplicity and uncertainty of the effectiveness variables, SE is not absolute nor deterministic
- It cannot be measured exactly by an instrument
- It is a probabilistic concept and it should be treated accordingly

Weapon System Effectiveness Industry Advisory Committee (WSEIAC)

- In 1963 the WSEIAC was organized to determine the effectiveness factors of weapon systems

WSEIAC Effectiveness Factors

- The WSEIAC identified three system effectiveness factors:
  - (1) Dependability (D)
  - (2) Capability (C)
  - (3) Availability (A)
- Effectiveness (E) is a measure of the extent to which a system may be expected to achieve a set of specific mission requirement, and is a function of “A”,”C”, and “D

Effectiveness of Multi-States Systems

- System with “n” states:

$$a_1, a_2, a_3, \ldots\ldots, a_n$$

$$E=[A][D][C]$$

$$= [a_1 \; a_2 \; \ldots\ldots \; a_n] \begin{bmatrix} d_{11} & d_{12} & \ldots\ldots & d_{1n} \\ d_{21} & & \ldots\ldots & d_{2n} \\ \vdots & & & \vdots \\ d_{n1} & & \ldots\ldots & d_{nn} \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix}$$

Effectiveness Framework

- System Effectiveness must account for limitations due to:
  - Degradation in system readiness
  - Physical failures due to hardware, operator, and/or software malfunction(s)
  - Design inadequacy

Two-States System

Single Shot Box

- Two States "OPERATIVE", or "NOT OPERATIVE"
  - Availabililty Matrix contains two elements

$$[A] = [a_1 a_2]$$

a_1 is probability that system is operable at time "t"

a_2 is probability that system is not operable at time "t"

$$a_1 = \frac{MTBF}{MTBF + MTTR} = P_{sr}$$

$$a_2 = \frac{MTTR}{MTTR + MTBF} = 1 - P_{sr}$$

Two-States System & No Repair

- Two-states system and no repair during mission
  - $P_{sr} = a_1$: Single shot prob. of success
  - Since no repair during mission; then
  - Dependability matrix is one element

$[D] = [d_{11}] = P_r$ = Mission Reliability

and

- Capability matrix is one element

$[C] = [c_1] = P_{da}$

Therefore,

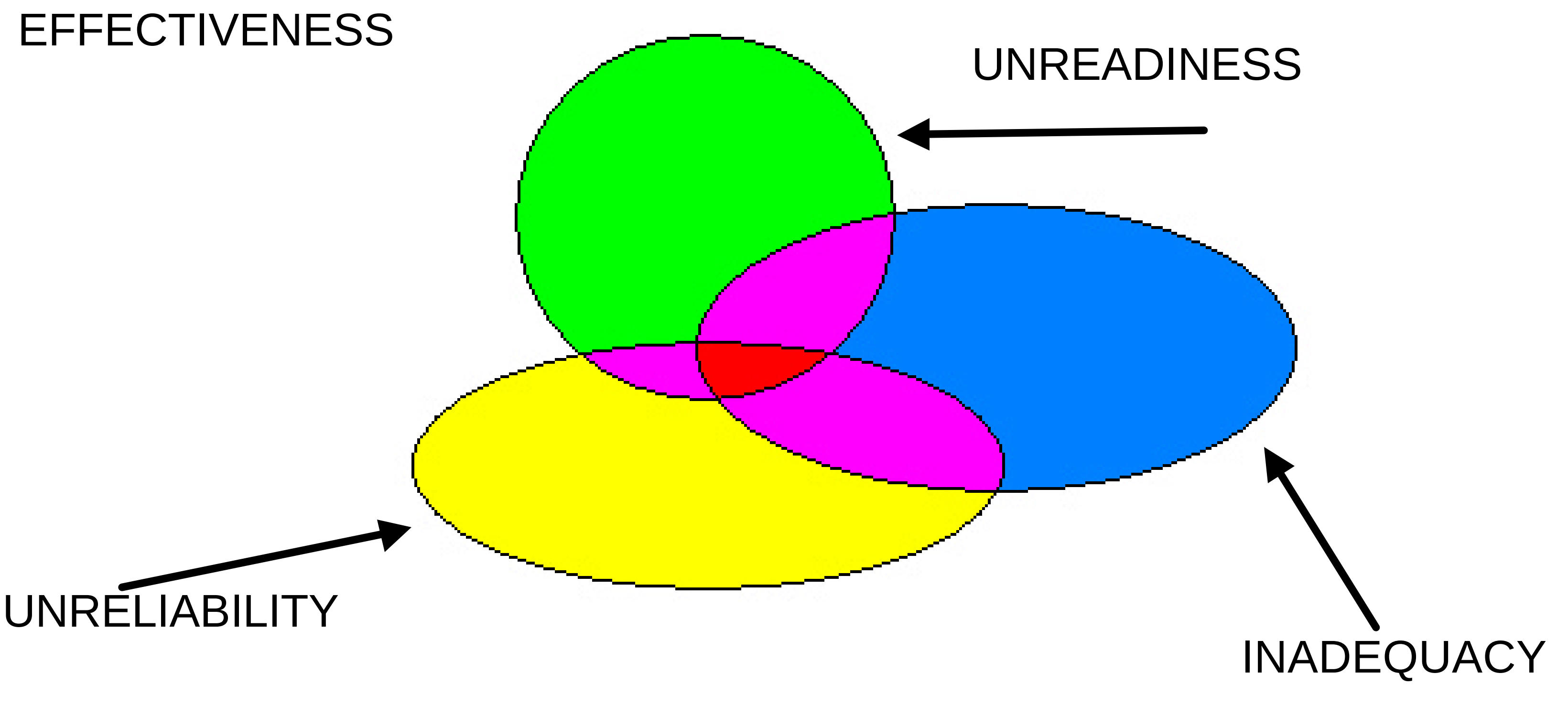
$$P_{se} = P_{sr} P_{da} P_r$$

Probabilistic Framework

$$P_{se} = P_{sr}P_{r}P_{da}$$

- P_{se}: Prob. that the system is effective
- P_{sr}: Prob. that the total system is ready to be operated and operates satisfactorily when used under specified conditions
- P_{da}: Prob. that the system will successfully accomplish its mission given it is operated within design specification
- P_r: Prob. that the system will not fail due to hardware, operator, and/or software failure
- Operator skills, stress, and proficiency are subsumed into P_{sr}, P_r, and P_{da}; or can be represented by a separate factor P_o

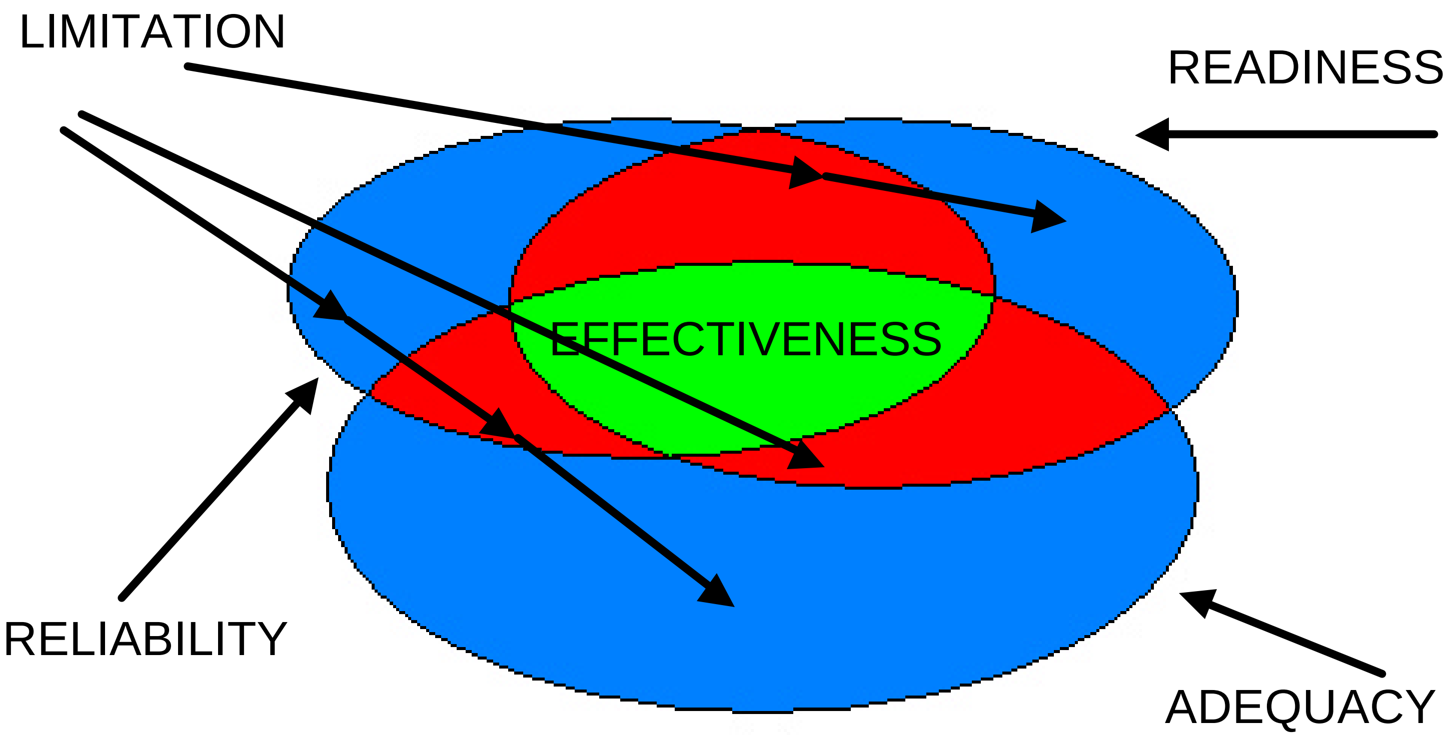
EULER DIAGRAM OF THE EFFECTIVENESS FACTORS



EVENTS DIAGRAM OF SYSTEM EFFECTIVENESS AND LIMITATION

- LIMITATION IS THE AREA BOUNDED BY THE NONOBVERLAPPING EDGES

EULER DIAGRAM OF THE EFFECTIVENESS FACTORS



EVENTS DIAGRAM OF SYSTEM EFFECTIVENESS AND LIMITATION

- SYSTEM EFFECTIVENESS IS THE INTERSECTION OF THE THREE SYSTEM EFFECTIVENESS REGION

Systems Effectiveness
Hardware and Software

- Systems Effectiveness of aircraft, car, missile, weapon system, software application, air traffic radar:
  - Performance / Capability
  - Reliability
  - Operational Readiness
- These factors are interrelated and must be dealt with together

System Measures

- System effectiveness is the term often used to describe the overall capability of a system to accomplish its mission
- Missile system: $P_{se} = P_{kss}$,
  - It does not kill if it is
  - 1) Unavailable or inoperable: this accounts for hardware and software failures and degradation in readiness
  - 2) Operable but fails to kill $\longrightarrow$ accounts for design limitation: inadequate velocity, range, and/or lethality

MOE

- MOE represents what can be expected from the system
- It must be in an operationally oriented form that can be readily understood and utilized
- MOE is any index which represents the quality of a system

MOE Can Be:

- A Measured physical parameter: velocity, range, length, payload, and # of tracks
- Quantity is calculated based on measurement: MTBF, MTTR, MPG, Profit, Production Rate, and MDT
- Quantity is predicted based on measurement: probability of survival, (P_k), Return-On-Investment (ROI), and Probability of Detection (P_d)

Desired Characteristics for Measures

Characteristics	Definition
Mission Oriented	**Relate to force/system mission**
Discriminatory	**Identify real differences between alternatives**
Measurable	**Able to be computed or estimated**
Quantitative	**Able to be assigned numbers or ranked**
Realistic	**Relate realistically to the system and associated uncertainties**
Objective	**Defined or derived, independent of subjective opinion. (It is recognized that some measures cannot be objectively defined)**
Appropriate	**Relate to acceptable standards and analysis objectives**
Sensitive	**Reflect changes in system variables**
Inclusive	**Reflect those standards required by the analysis objectives**
Independent	**Mutually exclusive with respect to other measures**
Simple	**Easily understood by the user**

Weapon System Effectiveness

- An air launched weapon system consists of the following:
  - A/C, missile, avionics, pilot, and target
  - Its effectiveness reflects the attributes of these elements
  - Its utility depends on how well it performs against the competition
  - Duel analysis is the method for comparing weapon system “A” to “B”

System Effectiveness Analysis (SEA)

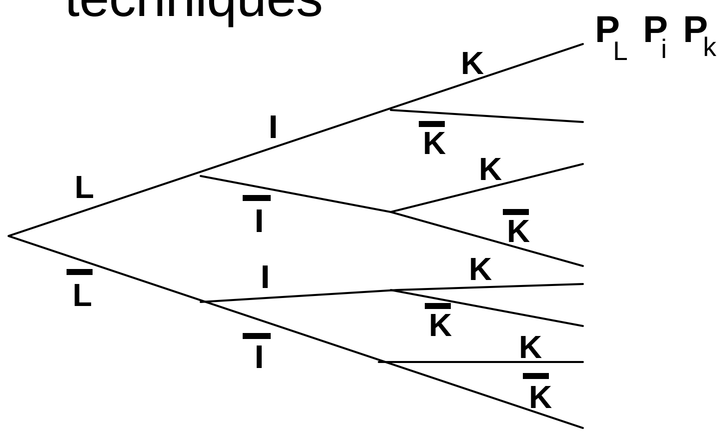
- SEA is an integral part of justifying, designing, and specifying systems
- SEA is performed:
  - On existing systems for a given scenario to gain insights on deficiencies and perform tradeoff analysis of “P I P” versus new and balanced design
  - SEA is integrated into the design process of new systems. Effectiveness is evaluated at every phase of the development process

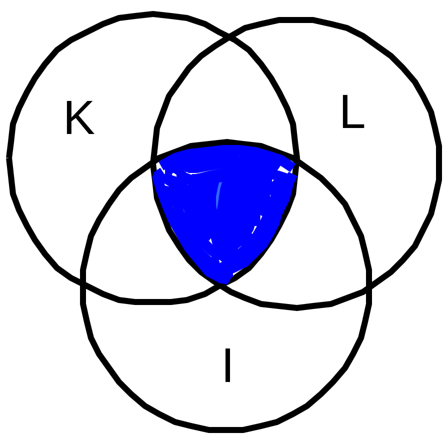
System Effectiveness Analysis Techniques
SEA - Techniques

- There are six generic types of SEA techniques:
  - 1) Analytical
  - 2) Monte Carlo
  - 3) Modeling and Simulation
  - 4) Case Study
  - 5) Polling – Consensus
  - 6) Mixed: A combination of some or all of the techniques
- These techniques have differences in:
  - Level of details
  - Inclusion of stochastic effects
  - Types of features considered – multi-modes, adaptability, hand-over

Analytical SEA

- Are used to analyze network-structured systems
- Using mathematical & probabilistic formulas calculate the probability of each branch in the network
- The outcome @ each terminal node is evaluated from the branch probabilities leading to the node
- The probabilities of similar outcomes are summed up to give the “MOE” of that outcome
- When applicable the analytical approach is superior to all other techniques





Effectiveness of Three-Phase System

- Truth table gives the possible outcomes.

T	H	K	Discussion
0	0	0	Possible: No Targeting, No Hit, and No Kill: $\bar{T}\,\bar{H}\,\bar{K}$
0	0	1	Impossible: No Targeting, No Hit, and Kill: $\bar{T}\,\bar{H}\,K$
0	1	0	Impossible: No Targeting, Hit, and No Kill: $\bar{T}\,H\,\bar{K}$
0	1	1	Impossible: No Targeting, Hi, and Kill: $\bar{T}\,H\,K$
1	0	0	Possible: Targeting, No Hit, and No Kill: $T\,\bar{H}\,\bar{K}$
1	0	1	Impossible: Targeting, No Hit, and Kill: $T\,\bar{H}\,K$
1	1	0	Possible: Targeting, Hit, and No Kill: $T\,H\,\bar{K}$
1	1	1	Possible: Targeting, Hit, and Kill: $T\,H\,K$

Monte Carlo: SEA

- Monte Carlo is a statistical tool used in simulation and is referred to as “variance reducing technique”
- It is used to analyze network structured systems to determine terminal node probabilities of random processes
- Probability of occurrence of an event is evaluated by using sampling methods
  - The probability distribution functions are created for each random process in the operation of the system
  - The distributions are used for sample generation using random number generators

Modeling and Simulation: SEA

- Many complex problems cannot be solved analytically
- Modeling and Simulation is an important tool of system designers: aircraft, plant layout, simulating lines of communication, weapon systems, and war games
- Simulation is the laboratory of analysts

  First Step: develop a model representing the system logical flow diagrams, interconnected elements with operating rules ,e.g., UML and Component-based Development

  Second Step: identify applicable distributions

  Third Step: Validation of the model is a must to establish credibility of the simulation

** Typical simulation models consist of a high number of elements, rules, and logical linkages

Abstraction Levels of Simulation Environments

Abstraction

4 Virtual Environment

3 Physics-Based Environment

2 Engineering-Based Environment (Hardware-in-the-Loop)

1 Real World Environment (Mock-ups)

Case Study: SEA

- Some systems are very complex and of special nature that the previous techniques are hard to apply
- Case study technique is used in studying corporations, societal systems, decision making processes, and MOE's determination
- The process requires going through records, performing interviews, sorting out the desired data, and analyzing the data

Polling – Consensus: SEA

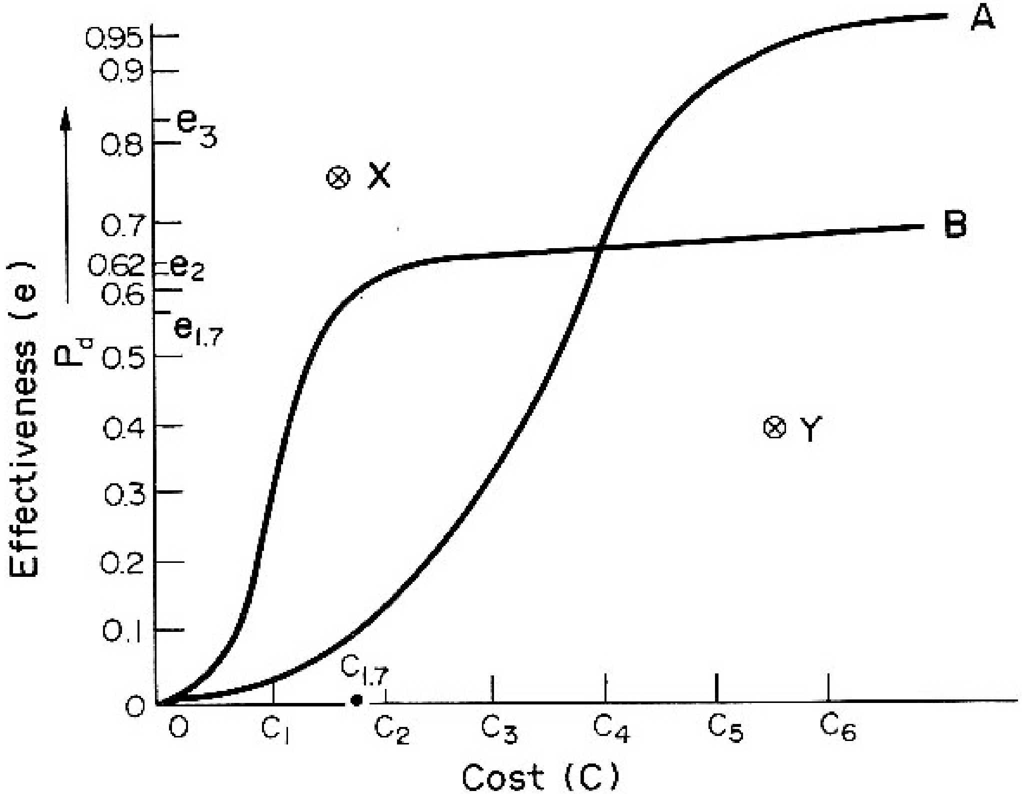
- The polling technique is used in establishing “MOE’s” of societal systems
- The first step is collecting the data by conducting interviews, questionnaires,….
- The second step is analyzing the data

Mixed: SEA

- A real world system effectiveness analysis will use more than one technique
- A typical “SEA” consists of the following steps:
  - 1) Perform system synthesis and partitioning to set-up the system operational flow
  - 2) Identify the processes associated with the sequence-of-event
  - 3) Formulate mathematical and stochastic models of the processes
  - 4) When applicable, use analytical and/or Monte Carlo techniques to evaluate the effectiveness
  - 5) Use simulation to represent complex operational scenarios
  - 6) Apply “Case Study” or polling techniques to derive effectiveness measures

Outcome of C. E.

- Specify ‘E’, then determine cost, or
- Specify ‘cost’ then determine ‘E’
- Strategy: set maximum cost at the knee of the curve



Tradeoff
Air Traffic Control Radar

- Two Options:
  - ‘A’ 2 TX to increase power and redundancy
  - ‘B’ 1 TX

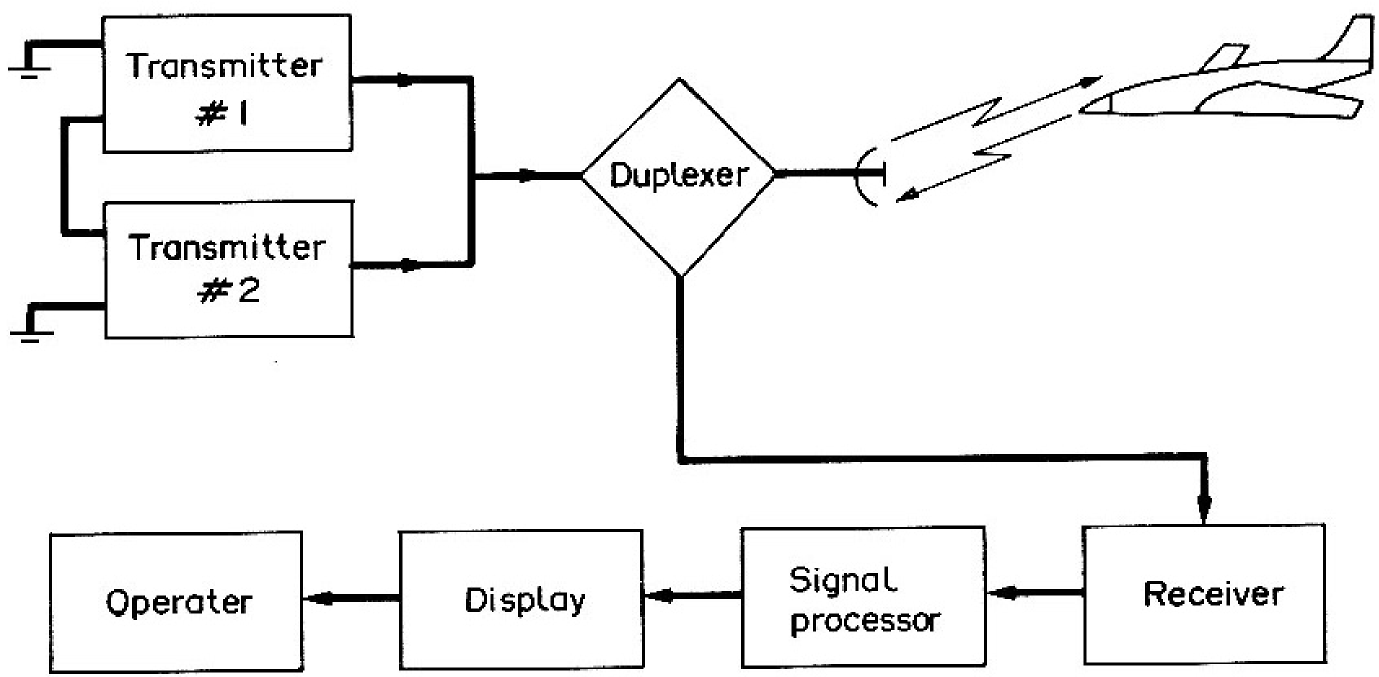


Fig. 1.10 Block diagram of an air traffic control radar.

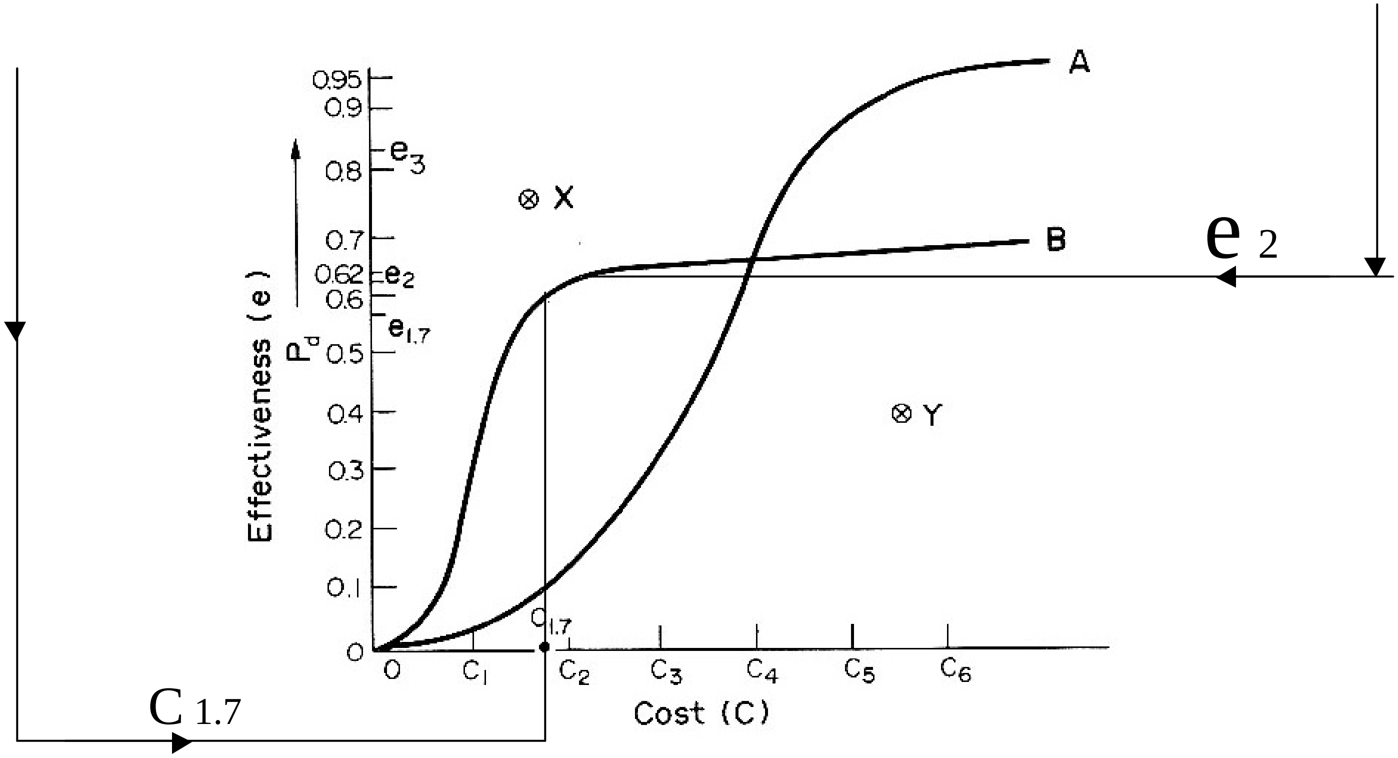
ATC-RADAR

- Option-B lost effectiveness at long ranges because:

  (1)lower power, and (2) lower reliability – no redundancy

* Option-B lost effectiveness at short ranges because of lower reliability

- If effectiveness level “e 2” = 0.62 is adequate, then “B” is the logical choice
- If cost is set @ “C 1.7”, then option “B” is the proper choice



Weapon System

An air launched weapon system consists of:

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Geometry Parameters

- OBA → Off boresight Angle
- ADL → Armament Data Line
- Tip-off Angle = k(OBS + ∝), 1 = K = 3
- Gimbal Angle = Tip-off Angle

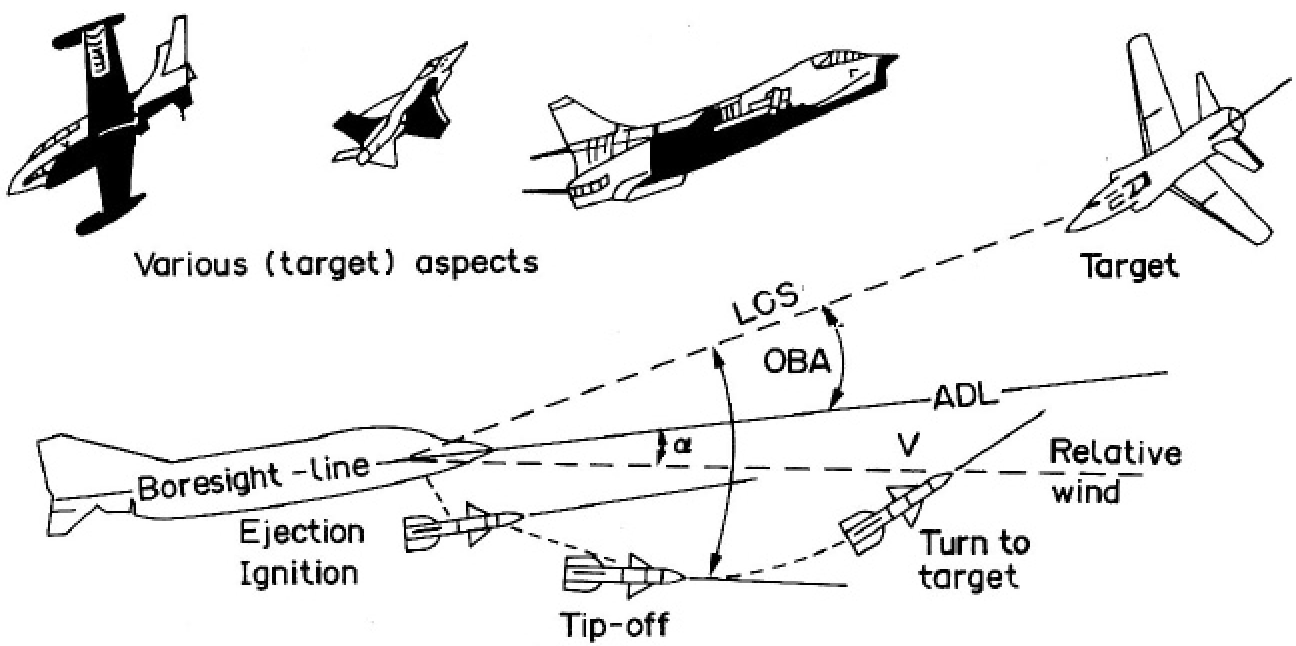


Fig. 2.6a Relationship between OBA, ADL, LOS, $\bar{V}$, α and tip-off angle. Tip-off angle = $\underline{k}$(OBA + α), where 1.0 ≤ $\underline{K}$ ≤ 3 is an empirical number, and gimbal angle ≥ tip-off angle to maintain lock-on.

Key Performance Parameters

System and Subsystem Parameters, Lock on Before Launch Air-To-Air Weapon System

Subsystem	Target Acquisition Pilot, Weapon	OFF–Boresight OFF – Axis At Launch	All – Aspect	Kinematics Aircraft, Target Missile	Miss Distance Intercept	Lethality	Physical Characteristics, Weight, Size, Shape
Target Characteristics Maneuverability Velocity, Size Radiation Cross Section							
Pilot Acquisition Avionics Aides Aircraft Maneuverability Stress/Fatigue							
Guidance and Control Seeker Sensitivity Resolution Tracking Rate Guidance Law							
Airframe and Propulsion Lift, Drag & Thrust -------------------------- Maneuverability | Angle of attack | C.G. Location Rmax, Rmin, maneuverability, Time to intercept, altitude							
Warhead and Fuse Warhead Type Warhead Weight Fuse Sensivity Fuse Accuracy							

Measures-of-Adequacy and System Parameters A/A Weapon System

Key Performance Parameters \ Measure-of-Adequacy	Before Launch	Intercept	End-Game
	P_{lo}	P_i	P_k
	LAR: Launch Acceptability Region	IAR: Intercept Acceptability Region	KAR: Kill Acceptability Region
Target Acquisition Reaction Time			
Off-Boresight Angle			
All-Aspect			
Intercept Miss Distance			
Kinematics Target Maneuverability Range Velocity and Altitude Aircraft Velocity, Maneuverability Missile Maneuverability RMAX, RMIN, Time to Intercept			
Lethality Warhead and Fuse Miss Distance			
Physical Parameters			

Relationship Matrix 1
Performance Parameters Versus Requirements
QFD

Relationship: Key Performance Parameter/Requirement

		Performance Parameters								
Requirement	Weighting Factor	Rotor FOM	Hover Ceiling	Rate of Climb	Vertical Rate of Climb	Dash Speed	Cruise Speed	Service Ceiling	Maneuver-ability	Vulner-ability
Reliability & Maintainability	1.0	0	0	0	0	0	0	0	1	1
Speed	0.94	2	1	1	1	3	1	1	2	2
Maneuverability	0.9	1	2	3	3	3	1	2	3	3
Range	0.85	1	1	1	1	1	2	1	1	1
Reduced Vibration	0.8	0	0	0	0	2	0	0	3	3
Payload	0.7	3	3	3	3	2	2	3	1	2
Easier to Fly	0.5	0	0	0	0	0	1	1	2	0

Conclusion

- Systems engineering is effective if it is comprehensive, taking a balanced account of all aspects of systems engineering: philosophical, operational, management and business, and technical and engineering aspects.

Backup

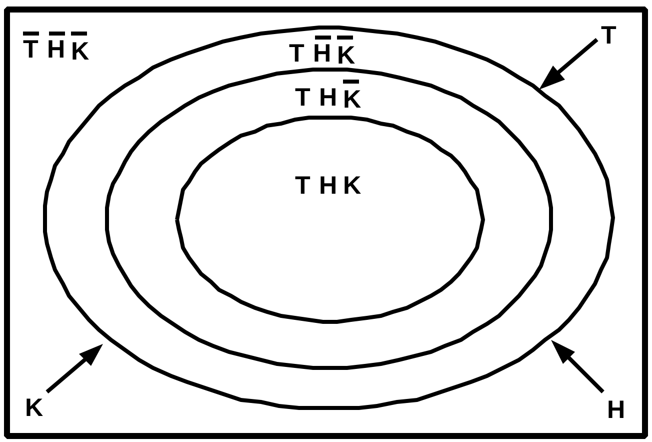
Three Phase Weapon System

•Targeting phase accounts for all pre-launch events, such as, target acquisition, tracking, designation….: T

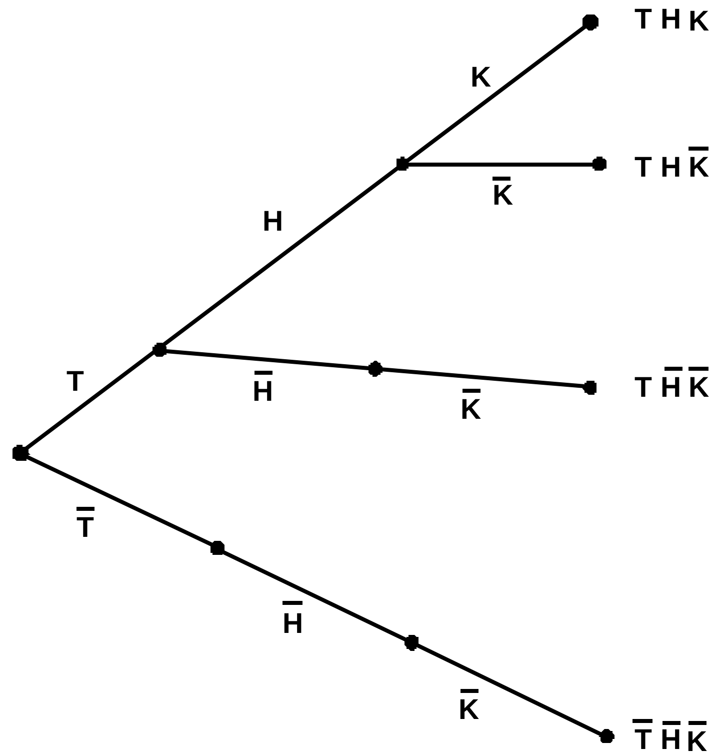
•Intercept; free flight or hit phase…: H

•End-game phase: interaction with target…: K

•Possible Outcomes:



(a)



(b)

(a) Events diagram of a three-phase weapon system

(b) Equivalent network diagram

(1) No targeting, No Hit, and No Kill: $\bar{T}\,\bar{H}\,\bar{K}$ (2) Targeting, No Hit, and No Kill: $T\,\bar{H}\,\bar{K}$

(3) Targeting, Hit, and No Kill: $T\,H\,\bar{K}$ (4) Targeting, Hit, and Kill: $T\,H\,K$

Effectiveness of Three-Phase System (cont.)

- The weapon system effectiveness events"e" are the compound event (THK), and

$$P_e = P_{kss} = P(THK) = P(T)P(H/T)P(K/TH)$$

$$= P(K)P(H/K)P(T/HK)$$

$$= P(K)\,(1.0)\,(1.0)$$

FOR EXAMPLE, IF $P(T) = .75$, $P(H/T) = .75$, and $P(K/TH) = .96$

$$P_e = P_{kss} = (.75)\,(.75)\,(.96) = .54$$

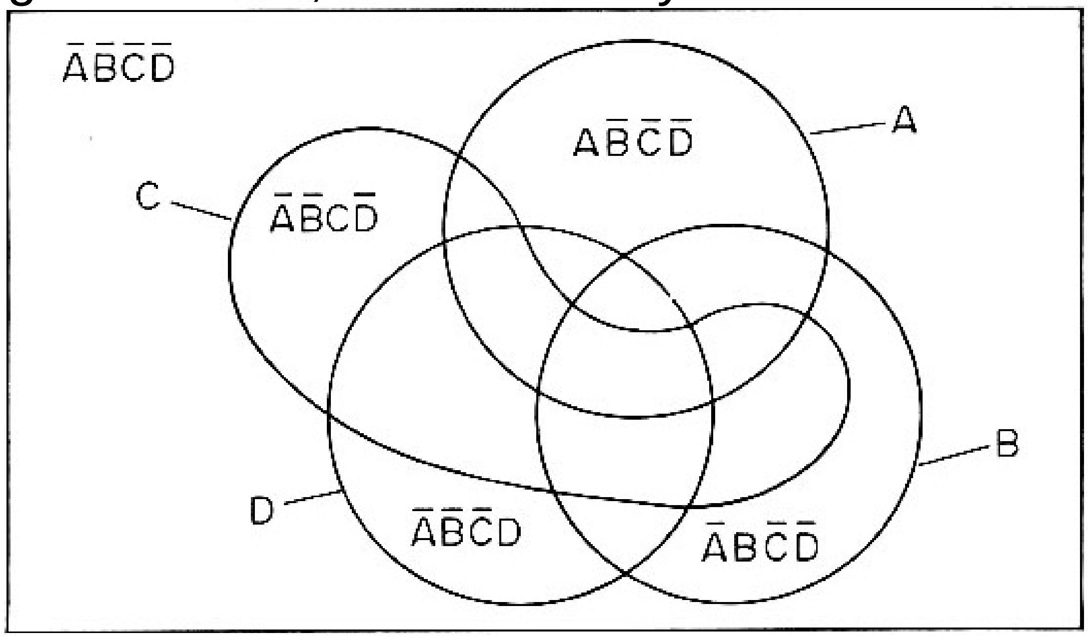
Modeling and Simulation Abstraction Levels

- Virtual level: components are represented by Input-Output models. Simulation consists of interconnected components.
- Physics-based level: a digital representation based on the physics of the building block is used instead of the virtual component.
- Engineering-based: real-world building blocks are used in the hardware-in-the-loop simulation.
- Real-world Mock-up: mock-up models of building blocks are used in a real world simulation environment.

Example

A ➔ OBS Limitation, B ➔ All-Aspect Limit

C ➔ Range Limitation, D ➔ Accuracy Limit



$$P_{da}(s) = P\,[A\ B\ C\ D]$$

Since A, B, C and D are statistically independent, then

$$P_{da}(s) = P(\bar{A})\cdot P(\bar{B})\cdot P(\bar{C})\cdot P(\bar{D})$$

$$= P(1-A)\ P(1-B)\ P(1-C)\ P(1-D)$$

$$= (.9)\ (.95)\ (.92)\ (.95)$$

$$= 0.747 \simeq 0.75$$

$$\underline{P}_{se} = \underline{P}_{da}\,\underline{P}_{r}\,\underline{P}_{sr} = \underline{P}_{lo}\,\underline{P}_{i}\,\underline{P}_{k}\,\underline{P}_{r}\,\underline{P}_{sr} \tag{2.18}$$

$$\left.\begin{aligned} &= [(1-\underline{P}_{lol})\,(1-\underline{P}_{il})\,(1-\underline{P}_{kl})\,(1-\underline{P}_{rl})\,(1-\underline{P}_{sr})] \\ &= \underline{P}[\underline{\bar{A}}\;\underline{\bar{B}}\;\underline{\bar{C}}\;\underline{\bar{D}}\;\underline{\bar{E}}] \\ &= \underline{P}(\underline{\bar{A}}/\underline{\bar{D}}\;\underline{\bar{E}})\;\underline{P}(\underline{\bar{B}}/\underline{\bar{A}}\;\underline{\bar{D}}\;\underline{\bar{E}})\;\underline{P}(\underline{\bar{C}}/\underline{\bar{A}}\;\underline{\bar{B}}\;\underline{\bar{D}}\;\underline{\bar{E}})\;\underline{P}(\underline{\bar{D}}/\underline{\bar{E}})\;\underline{P}(\underline{\bar{E}}) \end{aligned}\right\} \tag{2.19}$$